Tachyon Reconstruction of Ghost Dark Energy

A. Sheykhi • M. Sadegh Movahed • E. Ebrahimi

Abstract Recently it has been argued that a possible source for the dark energy may arise due to the contribution to the vacuum energy of the QCD ghost in a time-dependent background. In this paper we establish a connection between interacting ghost dark energy and tachyon field. It is demonstrated that the evolution of the ghost dark energy dominated universe can be described completely by a single tachyon scalar field. The potential and the dynamics of the tachyon field are reconstructed according to the evolutionary behavior of ghost energy density

Keywords tachyon; ghost; dark energy.

1 Introduction

Based on the plenty of observational evidences (Riess et al. 1998, 1999; Perlmutter et al. 1999; Kowalski et al. 2008), in the present time, it is accepted that the universe is undergoing a phase of accelerated expansion due to the presence of an unknown agent namely the "dark energy" (DE). Identifying the origin and nature of this unknown agent has been one of the great challenges in modern theoretical cosmology. Many different approaches have been proposed to solve the DE problem. These approaches can be

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mainly categorized in two distinct groups. First group are the modified gravity models which propose some serious modifications to Einstein's theory of gravity such as $f(R)$ gravity (Capozziello et al. 2003; Carroll et al. 2004; Nojiri and Odintsov 2007; Movahed et al. 2007; Baghram et al. 2009), scalar-tensor theories (Amendola 1999; Uzan 1999; Chiba 1999; Bartolo and Pietroni 2000), Quintessence model (Wetterich 2004; Movahed and Rahvar 2006; Rahvar and Movahed 2007; Cai et al. 2007) and so on. The second category are those support the idea of the existence of a strange type of energy whose gravity is repulsive and consist an un-clustered component through the universe. The first and simplest candidate for DE is the cosmological constant Λ which has constant equation of state (EoS) parameter $w = -1$ (Sahni and Starobinsky 2000). Although this model has a good agreement with observational data but it suffers several difficulties such as *fine tuning* and *coincidence* problem (Riess et al. 1998, 1999). Further observations detect a small variation in the EoS parameter of DE in favor of a dynamic DE. These observations show that the EoS of DE w is likely to cross the cosmological constant boundary -1 (or phantom divide), i.e. w is larger than -1 in the recent past and less than -1 today (Feng et al. 2005; Alam et al. 2004; Huterer and Cooray 2005). The conventional scalar-field model, the quintessence with a canonical kinetic term, can only evolve in the region of $w > -1$, whereas the model of phantom with negative kinetic term can always lead to $w \leq -1$. Neither the quintessence nor the phantom alone can realize the transition of w from $w > -1$ to $w < -1$ or vice versa. A comprehensive review on DE models can be seen in a very recent paper by M. Li, et al. (Li 2011).

An interesting model of DE, called "ghost dark energy" (GDE) was recently proposed (Urban and Zhitnitsky 2010; Ohta 2011). The so called "Veneziano ghost field" is presented as a solution to $U(1)$ problem in

effective low energy QCD (Witten 1979; Veneziano 1979; Rosenzweig et al. 1980; Nath and Arnowitt 1981; Kawarabayashi and Ohta 1980). The ghost field seems to be un-physical and has no contribution to the vacuum energy in the Minkowski spacetime. However, in a dynamic background or a spacetime with non-trivial topology the ghost field contribute to the vacuum energy proportional to $\Lambda_{QCD}^3 H$, where H is the Hubble parameter and Λ_{QCD}^3 is QCD mass scale (Ohta 2011). Actually the DE models based on the ghost field consider this vacuum energy density as a dynamical cosmological constant to investigate its role as an alternative to resolve the DE puzzle (Cai et al. 2010; Sheykhi and Movahed, 2011; Sheykhi and Bagheri 2011; Ebrahimi and Sheykhi 2011a,b). The ghost DE model can also categorized to the class of inhomogeneous fluid DE models (Nojiri and Odintsov 2005). One of the most important advantages of the ghost DE model is that this model comes from the standard model of particle physics and we do not need to introduce any new degree of freedom.

On the other hands, the tachyon field has been proposed as a possible candidate for DE. A rolling tachyon has an interesting equation of state whose parameter smoothly interpolates between -1 and 0 (Gibbons 2002). Thus, tachyon can be realized as a suitable candidate for the inflation at high energy (Mazumdar et al. 2001) as well as a source of dark energy depending on the form of the tachyon potential (Padmanabhan 2002). These motivate us to reconstruct tachyon potential $V(\phi)$ from GDE model. The correspondence between tachyon field and various dark energy models such as holographic dark energy (Setare 2007; Granda and Oliveros, 2009; Karami and Fehri 2010) and agegraphic dark energy (Sheykhi 2011; Karami et al. 2010) has been already established. The extension has also been done to the entropy corrected holographic and agegraphic dark energy models (Jamil and Sheykhi 2011).

The effective lagrangian for the tachyon field is given by (Sen 2002a,b)

$$L = -V(\phi)\sqrt{1 - g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}, \qquad (1)$$

where $V(\phi)$ is the tachyon potential. The corresponding energy momentum tensor for the tachyon field can be written in a perfect fluid form

$$T_{\mu\nu} = (\rho_\phi + p_\phi)u_\mu u_\nu - p_\phi g_{\mu\nu}, \qquad (2)$$

where ρ_ϕ and p_ϕ are the energy density and pressure of the tachyon, respectively. The velocity u_μ is

$$u_\mu = \frac{\partial_\mu\phi}{\sqrt{\partial_\nu\phi\partial^\nu\phi}}. \qquad (3)$$

It was demonstrated that dark energy driven by tachyon, decays to cold dark matter in the late accelerated universe and this phenomenon yields a solution to cosmic coincidence problem (Srivastava 2004). Choosing different self-interaction potentials in the tachyon field model leads different consequences for the resulted DE model.

The rest of this paper is organized as follows. The next section includes the relations and discussions about the reconstructed tachyon GDE model. In section III we extend the study to the interacting GDE model. The Summary and conclusion are given in section IV.

2 Tachyon ghost model

Consider a flat Friedmann-Robertson-Walker (FRW) which its dynamics is governed by the Friedmann equation

$$H^2 = \frac{1}{3M_p^2}(\rho_m + \rho_D), \qquad (4)$$

where ρ_m and ρ_D are the energy densities of pressureless matter and GDE, respectively. The ghost energy density is proportional to the Hubble parameter (Ohta 2011)

$$\rho_D = \alpha H. \qquad (5)$$

where α is a constant of order $\Lambda_{\rm QCD}^3$ and $\Lambda_{\rm QCD} \sim 100 MeV$ is QCD mass scale. We define the dimensionless density parameters as

$$\Omega_m = \frac{\rho_m}{\rho_{\rm cr}}, \quad \Omega_D = \frac{\rho_D}{\rho_{\rm cr}} = \frac{\alpha}{3M_p^2 H}, \quad , \qquad (6)$$

where the critical energy density is $\rho_{\rm cr} = 3H^2 M_p^2$. Using (6), the Friedmann equation can be rewritten as

$$\Omega_m + \Omega_D = 1. \qquad (7)$$

The conservation equations read

$$\dot{\rho}_m + 3H\rho_m = 0, \qquad (8)$$
$$\dot{\rho}_D + 3H\rho_D(1 + w_D) = 0. \qquad (9)$$

Taking the time derivative of relation (5) and using the Friedmann equation we find

$$\dot{\rho}_D = \rho_D\frac{\dot{H}}{H} = -\frac{\alpha}{2M_p^2}\rho_D(1 + u + w_D). \qquad (10)$$

where

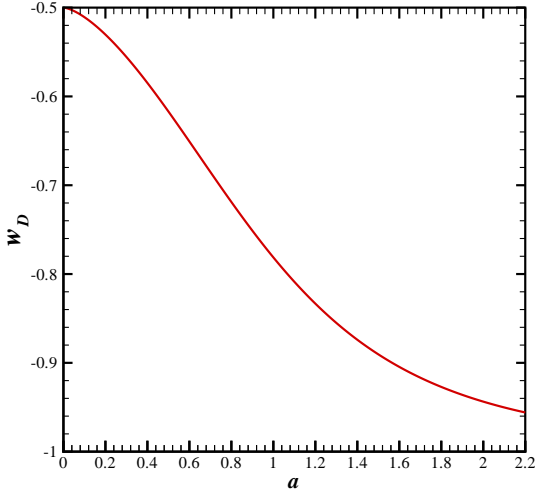$$u = \frac{\rho_m}{\rho_D} = \frac{\Omega_m}{\Omega_D} = \frac{1 - \Omega_D}{\Omega_D}, \qquad (11)$$

Fig. 1 The evolution of w_D for ghost dark energy. Here we have taken $\Omega_D^0 = 0.72$.

Fig. 2 The evolution of Ω_D for ghost dark energy where again we have taken $\Omega_D^0 = 0.72$.

is the energy density ratio. Inserting relation (10) in continuity equation (9), after using (11) we find

$$w_D = -\frac{1}{2 - \Omega_D}, \tag{12}$$

At the early time where $\Omega_D \ll 1$ we have $w_D = -1/2$, while at the late time where $\Omega_D \to 1$ the GDE mimics a cosmological constant, namely $w_D = -1$.

The equation of motion of GDE is obtained as (Sheykhi and Movahed, 2011)

$$\frac{d\Omega_D}{d\ln a} = 3\Omega_D \frac{(1 - \Omega_D)}{2 - \Omega_D}. \tag{13}$$

In Figs. 1 and 2 we have plotted the evolution of w_D and Ω_D versus scale factor a. From Fig. 1 we see that w_D of the GDE model cannot cross the phantom divide and mimics a cosmological constant at the late time.

Next we suggest a correspondence between ghost energy density and tachyon field. The energy density and pressure of tachyon field are given by

$$\rho_\phi = -T_0^0 = \frac{V(\phi)}{\sqrt{1 - \dot{\phi}^2}}, \tag{14}$$

$$p_\phi = T_i^i = -V(\phi)\sqrt{1 - \dot{\phi}^2}. \tag{15}$$

Thus the equation of state parameter of tachyon field is given by

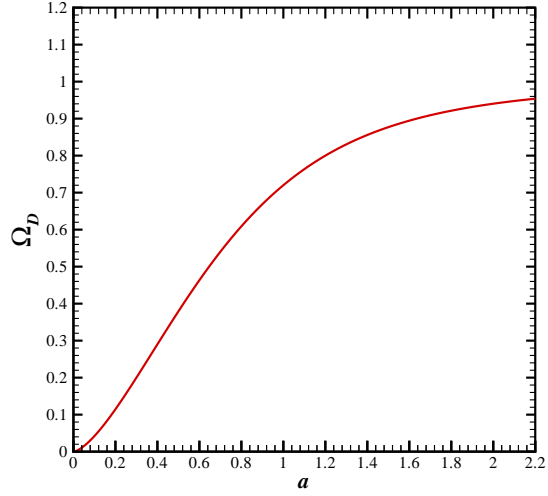$$w_\phi = \frac{p_\phi}{\rho_\phi} = \dot{\phi}^2 - 1. \tag{16}$$

To establish the correspondence between GDE and tachyon field, we equate w_D with w_ϕ. From Eqs. (12) and (16) we find

$$\dot{\phi}^2 = \frac{1 - \Omega_D}{2 - \Omega_D} \tag{17}$$

Using the second Eq.(6) as well as relation $\dot{\phi} = H\frac{d\phi}{d\ln a}$ we can rewrite the dynamics of scalar field as

$$\frac{d\phi}{d\ln a} = \frac{3M_p^2}{\alpha} \times \Omega_D \sqrt{\frac{1 - \Omega_D}{2 - \Omega_D}}. \tag{18}$$

Integrating yields

$$\phi(a) - \phi(a_0) = \frac{3M_p^2}{\alpha} \int_{a_0}^{a} \frac{da}{a} \Omega_D \sqrt{\frac{1 - \Omega_D}{2 - \Omega_D}}, \tag{19}$$

where $a_0 = 1$ is the present value of the scale factor. To reconstruct the tachyon potential, we identify $\rho_\phi = \rho_D = \alpha H$ and combine Eqs. (6) and (17) with (14). We find

$$V(a) = \frac{\alpha^2}{3M_p^2} \times \frac{\Omega_D^{-1}}{\sqrt{2 - \Omega_D}}. \tag{20}$$

Basically, from Eqs. (13) and (19) one can derive $\phi = \phi(a)$ and then combining the result with (20) one finds $V = V(\phi)$. Unfortunately, the analytical form of the potential in terms of the ghost tachyon field cannot be determined due to the complexity of the equations involved. However, we can obtain it numerically. The evolution of the field and the reconstructed tachyon potential $V(\phi)$ are plotted in Figs. 3 and 4, where we have taken $\phi(a_0 = 1) = 0$ for simplicity. From Fig. 3 we can
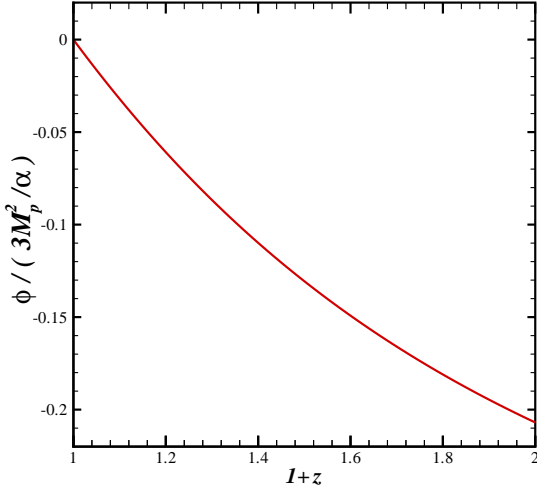
Fig. 3 The evolution of the scalar field ϕ as a function of redshift for tachyon ghost dark energy.
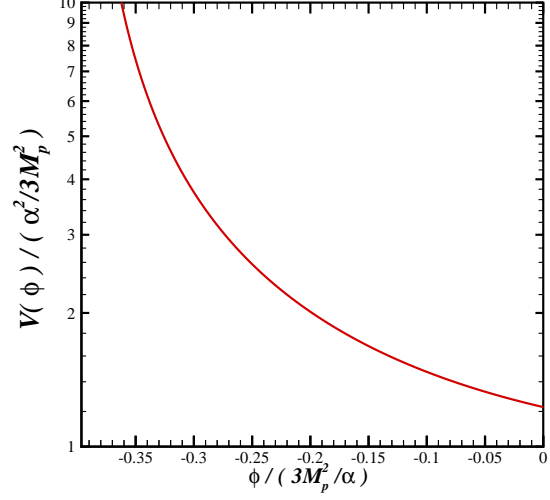

Fig. 4 The reconstructed potential $V(\phi)$ for tachyon ghost dark energy.

see the dynamics of the scalar field explicitly. In this figure we can see that the scalar field ϕ increases from below to zero at the present time which is not similar to other reconstructed models of DE. Fig. 4, indicates that the reconstructed scalar potential shows a nonzero minima which reminds the cosmological constant behavior of the model in the present time.

3 Interacting tachyon ghost model

In this section we extend our study to the interacting case. We shall assume the two dark components namely dark matter and GDE interact to each other thus, ρ_m and ρ_D do not conserve separately and evolve according to their semi conservation laws

$$\dot{\rho}_m + 3H\rho_m = Q, \tag{21}$$

$$\dot{\rho}_D + 3H\rho_D(1 + w_D) = -Q, \tag{22}$$

where Q represents the interaction term which can be, in general, an arbitrary function of cosmological parameters like the Hubble parameter and energy densities, $Q(H\rho_m, H\rho_D)$. The simplest choice is $Q = 3b^2 H(\rho_m + \rho_D)$ with b^2 is a coupling constant (Amendola et al. 2001; Zimdahl and Pavon 2001; Wang et al. 2005; Sheykhi 2009, 2010; Pavon and Zimdahl 2005; Banerjee and Pavon 2007). The positive b^2 is responsible for the energy transition from dark energy to dark matter. Sometimes this constant is taken in the range $[0, 1]$ (Zhang and Zhu 2006). Note that if $b^2 = 0$ then it represents the non-interacting FRW model while $b^2 = 1$ yields complete transfer of energy from dark energy to

dark matter. Recently, it is reported that this interaction is observed in the Abell cluster A586 showing a transition of dark energy into dark matter and vice versa (Bertolami et al. 2007). Observations of cosmic microwave background and galactic clusters show that the coupling parameter $b^2 < 0.025$, i.e. a small but positive constant of order unity (Ichiki et al. 2008), a negative coupling parameter is avoided due to violation of thermodynamical laws. Therefore the theoretical interacting models are phenomenologically consistent with the observations. It should be noted that the ideal interaction term must be motivated from the theory of quantum gravity. In the absence of such a theory, we rely on pure dimensional basis for choosing an interaction Q. Thus we take the interaction term of the following form

$$Q = 3b^2 H(\rho_m + \rho_D) = 3b^2 H\rho_D(1 + u). \tag{23}$$

Inserting Eqs. (10) and (23) in Eq. (22) and using (11) we obtain the equation of state parameter of interacting GDE

$$w_D = -\frac{1}{2 - \Omega_D}\left(1 + \frac{2b^2}{\Omega_D}\right). \tag{24}$$

In the late time where $\Omega_D \to 1$, the equation of state parameter of interacting GDE necessary crosses the phantom line, namely, $w_D = -(1 + 2b^2) < -1$ independent of the value of coupling constant b^2. At the present time with $\Omega_D^0 = 0.72$ the phantom crossing can be achieved provided we take $b^2 > 0.1$.
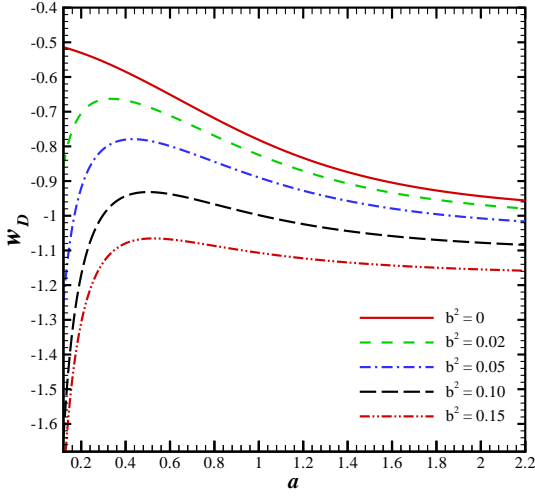
Fig. 5 The evolution of w_D for interacting ghost dark energy and different interacting parameter b^2.

Fig. 6 The evolution of Ω_D for interacting ghost dark energy. Selected curves are plotted for different b^2.

The equation of motion of interacting GDE can be obtained as (Sheykhi and Movahed, 2011)

$$\frac{d\Omega_D}{d\ln a} = \frac{3}{2}\Omega_D \left[1 - \frac{\Omega_D}{2 - \Omega_D}\left(1 + \frac{2b^2}{\Omega_D}\right)\right]. \tag{25}$$

The dynamics of w_D and Ω_D are plotted in Figs. 5 and 6. Selected curves are plotted for different value of the coupling parameter b^2. According to figure 6, one finds that in the future Ω_D continue approaching to 1 which shows that in this model of DE the future evolution of the universe is determined by the dark energy component. This indicates that probably the fate of the universe goes toward a big rip.

Having Eqs. (24) and (25) at hand, we are in a position to implement a correspondence between interacting ghost energy density and tachyon scalar field model, by comparing the ghost density with the tachyon field model and equating the equation of state parameter of this model with the equation of state parameter of interacting GDE obtained in (24). To this end, we equate w_D with w_ϕ. From Eqs. (24) and (16) we find

$$\dot{\phi}^2 = \frac{1}{2 - \Omega_D}\left(1 - \Omega_D - \frac{2b^2}{\Omega_D}\right). \tag{26}$$

Using second Eq. (6) as well as relation $\dot{\phi} = H\frac{d\phi}{d\ln a}$ we can rewrite the dynamics of scalar field as

$$\frac{d\phi}{d\ln a} = \frac{3M_p^2}{\alpha} \times \Omega_D \sqrt{\frac{1}{2 - \Omega_D}\left(1 - \Omega_D - \frac{2b^2}{\Omega_D}\right)} \tag{27}$$
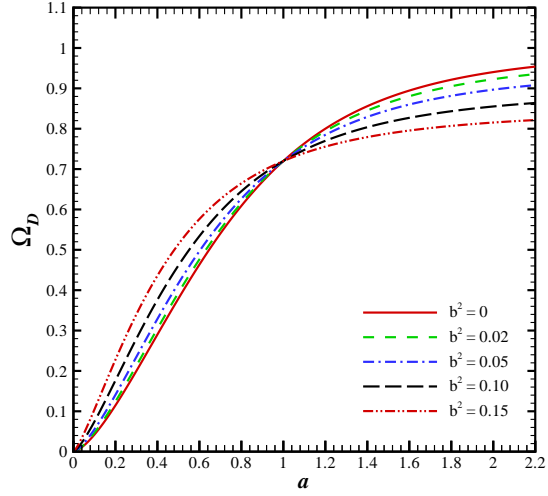
Integrating yields

$$\phi(a) - \phi(a_0) = \frac{3M_p^2}{\alpha}\int_{a_0}^{a} \frac{da}{a}\sqrt{\frac{\Omega_D^2}{2 - \Omega_D}\left(1 - \Omega_D - \frac{2b^2}{\Omega_D}\right)}. \tag{28}$$

where $a_0 = 1$ is the present value of the scale factor. To reconstruct the tachyon potential, we identify $\rho_\phi = \rho_D = \alpha H$ and combine Eqs. (6) and (26) with (14). The result is

$$V(\phi) = \frac{\alpha^2}{3M_p^2} \times \frac{1}{\Omega_D}\left(\frac{1 + 2b^2\Omega_D^{-1}}{2 - \Omega_D}\right)^{1/2}, \tag{29}$$

The evolutionary form of the tachyon field and the reconstructed tachyon potential $V(\phi)$ are plotted in Figs. 7 and 8. Again we have taken $\phi(a_0 = 1) = 0$ for simplicity. Selected curves are plotted for different value of the coupling parameter b^2. From these figures we find out the reconstructed scalar field has a same dynamic as the non-interacting case. For different choices of the coupling parameter b^2 we find a faster rate of evolution when b^2 increases. The reconstructed scalar potentials in Fig. 8 generally show decreasing and flattening in the near epoches. As the non-interacting case the scalar potential has a non-zero minimum which leads to an EoS parameter close to -1 for present time and near future. If the future evolution of the potential has a mirror image behavior of the plotted regions we can see that increasing b^2 leads to steeper and steeper form of potentials. In this form of potentials, the scalar field oscillates around a minima and settles down in the minima. The oscillation around the minima for ϕ^2-like potentials (with suitable choice of b^2) is completely
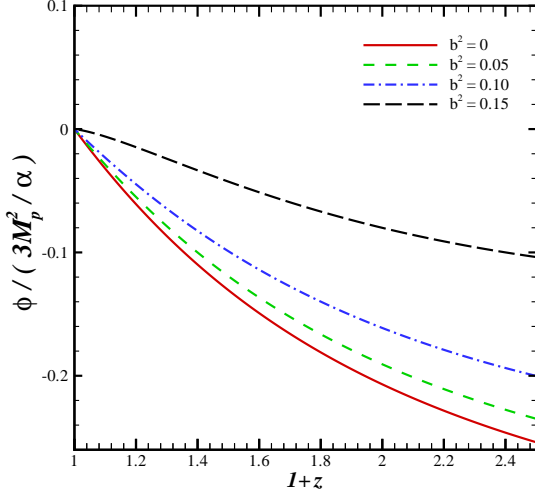
Fig. 7 The evolution of the scalar field ϕ as a function of redshift for interacting tachyon ghost dark energy and different coupling parameter b^2.

Fig. 8 The reconstructed potential $V(\phi)$ for interacting tachyon ghost dark energy and different coupling parameter b^2.

harmonic and can acts as pressureless fluid during the oscillation period of the scalar file as an alternative to cold dark matter.

4 Conclusion

The so called "ghost dark energy" was recently proposed to explain the dark energy dominated universe. In a dynamic background or a spacetime with non-trivial topology the ghost field contribute to the vacuum energy proportional to $\Lambda_{QCD}^3 H$, where H is the Hubble parameter and Λ_{QCD}^3 is QCD mass scale. A suitable choice of the H and Λ_{QCD} leads to right value of $\rho_D = \alpha H$. The advantages of this new proposal compared to the previous dark energy models is that it totally embedded in standard model so that one does not need to introduce any new parameter, new degree of freedom or to modify general relativity.

On the other hand, we know that the scalar field models of dark energy can be considered as an effective theory of the underlying theory of dark energy. This point motivated us to reconstruct the tachyon model of dark energy based on the ghost energy density. To this end, we have constructed a version of tachyon dark energy which mimics the behavior of the ghost model of dark energy in the early epochs and late time. Different quantities are plotted and evolution of the model is shown in different epochs. Due to importance of correspondence between these models (GDE and tachyon), one can mention the cosmological constant-like behavior of both of models in the late time. Another result of
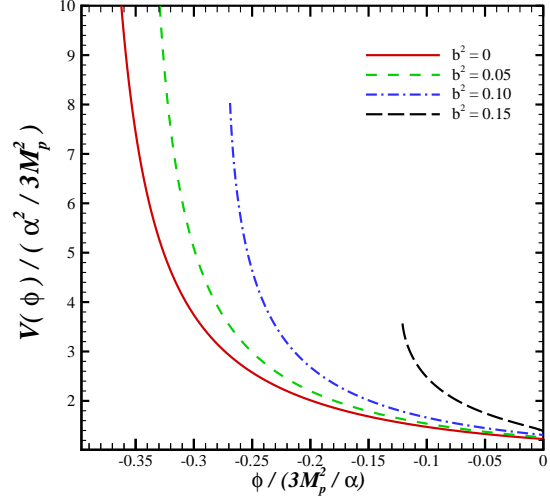
this correspondence is approaching of the reconstructed scalar field to zero from below which is different with respect to the other scalar field models.

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